

Buoyant Flows in Shafts  
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Introduction

The motions of buoyant flows contained within vertical shafts are being investigated in an experimental program that will lead to a prediction of the transport of heat and toxic materials within shafts due to buoyancy controlled mixing and the stack effect when the influence of heat transfer to the walls of the shaft can not be neglected. This work is based in part on the earlier experiments of Cannon, J. B. and Zukoski, E. E. (1975).

In this program, the basic flow under investigation is the motion of hot air within a vertical shaft and the subsequent heat transfer when the shaft is completely closed except at the bottom. The shaft and a mixture of air and carbon dioxide within it are initially at room temperature; the flow of interest is started when the bottom of the shaft is suddenly opened and is exposed to a reservoir filled with hot gas that is held at a constant temperature. The penetration of the hot air into the shaft in a vertical direction and the subsequent development of gas temperature, heat transfer to the walls from the hot gas, and removal of the carbon dioxide are then measured as a function of time. Configurations with windows that allow the stack effect to become the dominant flow are also being studied.

Experiments are carried out in an aluminum walled shaft 0.25 m square and 2.54 m high, and the bottom of the shaft can be suddenly exposed to air at temperatures up to 140° C. Heat transfer gages and thermocouples are used to determine heat transfer and the gas and wall temperature, and the transport of carbon dioxide within the shaft is studied to determine the transport processes within the gas column.

The flow can be divided into a relatively short *transient regime* or initial flow, some 10's of seconds, during which the hot gas front reaches the top of the shaft, and a *steady state regime* in which the time averaged gas temperature and heat transfer rates become constant. In the latter regime, fluctuations of up to 20 % about the time averaged values are observed. A quasi-steady state is reached because the walls of the duct have a very large heat capacity. The slow rise in surface temperature produced by the heat transfer is accompanied by a corresponding slow rise in the gas temperature for periods of 20 m.

The aim of this work is to develop models for predicting the motion of the initial front in the shaft, and the gas temperature field within the shaft, the rate of heat transfer to the walls, and the rate of transport of gas species within the shaft.

Closed Shaft Experiments

When the shaft is only open at the bottom, the transport of species and energy occurs because of a turbulent mixing process that is driven by the positive density gradient in the vertical direction. This produces a gravitational unstable configuration that feeds energy into a turbulent motion in the gas within the shaft. The instability is also driven by the heat transfer to the walls of the shaft which also produces an unstable density gradient in the gas near the wall.

The transport of species within the shaft is much slower and the transient period lasts for much longer periods. Models for both heat and species transfer rates are being developed.

The Nusselt number  $Nu \equiv \frac{h_c W}{k}$ , based on the shaft width  $W$ , and thermal conductivity of the gas  $k$ , and the heat transfer coefficient  $h_c$ , were about 60 for a wide range of conditions used for these closed shaft experiments and a correlation for the data is being sought. The dependence on the Grashof numbers, shown below for the stack

effect cases, does not fit the closed shaft data very well although the values for the Nusselt numbers were almost equal.

### Stack Effect Experiments

The stack effect is present when an opening in the shaft allows the gas within the shaft to communicate with the outside pressure field. Consider a shaft open at the bottom and filled with a gas with an average density  $\bar{\rho}$  when the density outside the shaft is  $\rho_{\infty}$ . If the bottom of the shaft is at the local ambient pressure, the pressure difference produced at a window that is  $H$  above the bottom of the shaft will be  $(\rho_{\infty} - \bar{\rho})gH$  and the mass flux per unit area of the window will be given by

$$\left[ \rho_{\text{window}} \right] \sqrt{2 \left( \frac{\rho_{\infty} - \bar{\rho}}{\rho_{\text{window}}} \right) gH}. \text{ In our experiments, fluid is withdrawn the shaft through the window and passed}$$

through a metering system so that a known flow can be established. Both the *transient* and *state regimes* are again established in the shaft. The influence of the mass withdrawal rate on the heat transfer and species transport within the shaft have been measured for flow rates that are 100, 50, and 25% of that given above. The window is at the top of the shaft and the area is 16% of the shaft area.

The turbulent mixing process still dominates this flow and correlations of the data for a wide range of conditions can be correlated by the simple relationship for the heat transfer coefficient:

$$Nu \equiv \frac{h_c Z}{k} = 0.13 (Gr_z Pr)^{\frac{1}{3}} \quad \text{when} \quad Gr_z Pr = \left( \frac{g \beta \Delta T Z^3}{\nu^2} \right) \left( \frac{C_p \mu}{k} \right)$$

Grashof numbers, based on the height above the bottom of the shaft,  $Z$ , are between  $8 \times 10^8$  and  $3 \times 10^{10}$ .

Our experimental data fits this correlation, based on data obtained with flows inside circular cylinders, to within 20%. Modeling will be simplified because the length scale drops out of the correlation since  $Z$  is linear on both sides and consequently the heat transfer coefficient becomes independent of the vertical scale; however, the dependence of heat transfer on the temperature of the gas and wall is strong. The range of conditions for both sets of experiments are being extended so that better models for these types of flow can be developed.

The transport of gas species vertically in the shaft are also being studied with the aim of producing a correlation.

### References:

Cannon, J. B. and Zukoski, E. E. (1975) *Turbulent Mixing in Vertical Shafts Under Conditions Applicable to Fires in High Rise Buildings*, Technical Fire Report No. 1 to the National Science Foundation, California Institute of Technology, Pasadena, California.

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